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COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS

JUNE 1973



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Prepared under Contract No. NAS 8-28377
by Biotechnology and Power Department
McDonnell Douglas Astronautics Company
Huntington Beach, California

for

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By
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FOREWORD

A Cost Analysis of Life Support Systems Study has been conducted by the Biotechnology and Power Department of the McDonnell Douglas Astronautics Company (MDAC), Huntington Beach, California, under Contract NAS8-28377. This project was performed for the NASA-Marshall Space Flight Center under the direction of Mr. James Moses, Deputy Chief, Life Support and Environmental Branch (S&E-ASTN-P).

The final report consists of a summary and four volumes each dealing with a specific life support system area as follows:

<u>Title</u>	<u>Report Number</u>
SUMMARY REPORT	MDC G4630
COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS	MDC G4631
COST ANALYSIS OF WATER RECOVERY SYSTEMS	MDC G4632
COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS	MDC G4633
COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS	MDC G4634

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Section 1

INTRODUCTION AND SUMMARY

The design and development of equipment for flight use in earth-orbital programs, when optimally approached cost effectively, proceed through the following logical progression: 1) bench testing of breadboard designs, 2) the fabrication and evaluation of prototype equipment, 3) redesign to meet flight-imposed requirements, and 4) qualification and testing of a flight-ready system. Each of these steps is intended to produce the basic design information necessary to progress to the next step. The cost of each step is normally substantially less than that of the following step. An evaluation of the cost elements involved in each of the steps cited above and their impact on total program cost are presented in this study.

In order to assist NASA/MSFC in long-range planning and allocation of resources in a cost effective manner in support of earth orbital programs, a methodology was developed to predict the relevant contributions of the more intangible cost elements encountered in the development of flight qualified hardware based on an extrapolation of past hardware development experience. Major items of costs within life support systems were identified and related to physical and/or performance criteria. Cost and performance data from Gemini, Skylab, and other aerospace and biotechnology programs were analyzed to identify major cost elements required to establish cost estimating relationships for advanced life support subsystems.

This report deals with the cost analysis of four leading oxygen recovery subsystems which include two carbon dioxide reduction subsystem, namely Sabatier and Bosch, and two water electrolysis subsystems, namely, the solid polymer electrolyte and the circulating KOH electrolyte.

The four oxygen recovery systems have been quantitatively evaluated. System characteristics, including process flows, performance and physical characteristics were also analyzed. Additionally, the status of development of each of the systems considered and the required advance technology efforts required to bring conceptual and/or pre-prototype hardware to an operational prototype status were defined. The equipment classification used based on the degree of refinement were as follows: 1) working model, 2) low-fidelity prototype, 3) high-fidelity prototype, and 4) flight-qualified system.

The most cost effective development approach was discovered to be with the programs that initially used working models and subsequently low-fidelity prototypes to verify concept workability. The further continuation of the development of the best approaches in the advanced research and technology phase from the low-fidelity to high-fidelity level had the potential of further reducing costs prior to committing funds to produce flight-qualified hardware. It was apparent that the high-fidelity hardware should be included in the advanced research and technology phase to provide the data required to minimize design changes in the flight production and qualification program. Design changes that occur too late in the development cycle will significantly escalate costs. The advanced research and technology phase, when effectively used, as previously discussed, has the overall effect of improving the production hardware development schedule and reducing the total program cost, including the expense of hardware, system certification, and testing.

The system costs were determined based on the summation of the average derived cost of each individual component for a given subsystem configuration. The system program costs were proportioned based on past recorded Gemini program experience. Cost of low- and high-fidelity oxygen recovery system prototypes were also evaluated and found to average approximately 5% and 10% respectively, of the cost of flight-qualified units. Resulting cost data agreed favorably with past equipment costs for other low- and

high-fidelity prototype hardware developed in advanced research and technology programs. The cost analysis of oxygen recovery systems is presented in the following Sections:

Cost Estimating Techniques

Cost Estimates of Oxygen Recovery Systems

Conclusions

Section 2

COST ESTIMATING TECHNIQUES

Cost estimations were established for both low- and high-fidelity prototypes and flight-qualified-type oxygen recovery hardware utilizing the methodology discussed below.

2.1 COST ESTIMATES OF OXYGEN RECOVERY SYSTEM PROTOTYPES

The cost of low-fidelity oxygen recovery system prototypes was found to depend on its degree of sophistication and utilization of available space hardware and/or commercial components. A cost estimate approximately equal to half that of a corresponding high-fidelity prototype was allocated to low-fidelity prototypes. High-fidelity prototypes were assumed to be similar in construction to the first test system produced in a flight program which has not undergone any qualification or reliability testing. The cost of the high-fidelity prototype was obtained by excluding those cost items which are pertinent solely to flight articles. Cost of low- and high-fidelity prototypes constituted 5% and 10%, respectively, of the cost of a corresponding flight-type system. A more detailed discussion of prototype cost estimating is presented in Report No. MDC G4630, "Cost Analysis of Life Support Systems - Summary Report".

2.2 COST ESTIMATES OF FLIGHT-QUALIFIED OXYGEN RECOVERY SYSTEMS

The oxygen recovery systems cost estimating techniques were developed by 1) identifying the physical and performance characteristics of each of the system components, 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered, and 3) the summation of equations for respective system components to establish the total system cost estimating. The U. S. Bureau of Standards Consumer Price Index was used to account for inflation and economic escalation.

The methodology used in the development of CER's is as follows:

1. The components were analyzed to determine which physical or performance characteristics might prove useful as predictive variables.
2. Costs were arrayed graphically against the candidate variables either singly or grouped. The most promising of these arrays were selected on the basis of a subjective analysis which considers the appropriateness of the variables, the form and slope of the curves, and the relative aspects of the component costs.

The derivation of a typical life support component CER is presented in detail in Report No. MDC G4630. Individual CER's for respective system components were summed up to establish the total system cost estimation. A summary of the CER's developed for oxygen recovery systems is presented in Table I. The validity of derived CER's was verified when they were applied to a number of Skylab components and were found to agree favorably with actual cost data.

A system schematic and a component identification list were prepared for each of the four oxygen recovery systems. System and process descriptions, including system performance and characteristics, were also given. The physical and performance parameters were identified for use in formulating the cost estimating relationships. Recurring CER's were then developed and computed for each of the system subassemblies and summed up to obtain the integrated system recurring cost estimates. The system's non-recurring CER's were computed on an integrated system basis. The major influencing parameter for the non-recurring CER's was found to be the number of component types in the system.

2.3 COST ELEMENT STRUCTURE

The cost element structure, comprising the detailed recurring and non-recurring cost function, provides visibility of the total project expenditures and permits identification of the significant project costs. The definition of cost-related terms used in this report is given in Section 2.5.

TABLE I - OXYGEN RECOVERY SUBSYSTEM
RECURRING COST ESTIMATING

ASSEMBLY	COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)
A. SABATIER CO₂ REDUCTION SUBSYSTEM	
1. Reactor Assembly	$C = 159 W_p^{0.267} N^{1.905} + 3900 W_{oc}$
2. Blower	$C = 38.2 P^{0.942} + 2192 W_{oc}$
3. Condenser/Separator	$C = 159 W_p^{0.267} N^{1.905} + 2959 W_{oc}$
4. Accumulator	$C = 1,918 V^{0.267} + 2959 W_{oc}$
5. Pump	$C = 91 P_v^{0.942} + 670 W_{oc}$
6. Controller	$C = 4795 W$
B. BOSCH CO₂ REDUCTION SUBSYSTEM	
1. Reactor Assembly	$C = 159 W_p^{0.267} N^{1.905} Q^{0.89} + 3900 W_{oc}$
2. Compressor	$C = 38.2 P^{0.942}$
3. Condenser/Separator	$C = 159 W_p^{0.267} N^{1.905} + 2959 W_{oc}$
4. Accumulator	$C = 1918 V^{0.267} + 2959 W_{oc}$
5. Pump	$C = 91 P_v^{0.942} + 670 W_{oc}$
6. Controller	$C = 4795 W$
C. SPE ELECTROLYTE SUBSYSTEM	
1. Electrolysis Modules	$C = (6250 W_M + 2192 W_{oc} + 2000) Q^{0.89}$
2. Pumps	$C = 91 P_v^{0.942} Q^{0.89} + 670 W_{oc}$
3. Deionizers	$C = 200 W_{oc} Q^{0.89} + 670 W_{oc}$
4. Power Conditioner/Coldplate	$C = (14.9 P^{0.942} + W_p^{0.267} N^{1.905}) Q^{0.89}$
5. Condenser/Separator	$C = 159 W_p^{0.267} N^{1.905} Q^{0.89} + 2959 W_{oc}$
D. CIRCULATING KOH ELECTROLYTE SUBSYSTEM	
1. Electrolysis Modules	$C = (6250 W_M + 2000) Q^{0.89} + 2192 W_{oc}$
2. Electrolysis Modules	$C = 38.2 P^{0.942} + 2192 W_{oc}$
3. Reservoir	$C = 1918 V^{0.267} + 2959 W_{oc}$
4. Pumps	$C = 91 P_v^{0.942} Q^{0.89} + 670 W_{oc}$
5. Heat Exchanger	$C = 159 W_p^{0.267} N^{1.905} + 2959 W_{oc}$

$$\text{TOTAL HARDWARE COST } C_T = \sum_{Q=1}^N F_A F_I \left(\sum_{I=1}^M C_I \right) Q^{(1-B)} \quad \text{DOLLARS}$$

WHERE,

N = NUMBER OF UNITS PURCHASED

F_A = COMPONENT ASSEMBLING FACTOR

F_I = ASSEMBLY INTEGRATION FACTOR

M = NUMBER OF COMPONENTS IN ASSEMBLY

C_I = COMPONENT FABRICATION COST

B = LEARNING CURVE SLOPE

Table II presents a breakdown of typical life support system expenditures, as encountered in the Gemini Program, divided in the respective recurring and non-recurring items. The major recurring cost item is that of flight hardware production. The major non-recurring costs are those related to Design, AGE, and Prime Contractor's specification and procurement efforts.

2.4 EFFECT OF INFLATION ON COST ESTIMATES

A major inherent feature of the methodology which is highly critical to the accuracy of the results obtained pertains to inflation and economic escalation. Since computed CER's are based on specific year dollars, they must be inflated to the proper year in order to obtain realistic future program values. Due to the lack of a specific aerospace price index, the yearly dollar value adopted in this report was considered to correspond to the Consumer Price Index shown in Figure 1, based on data published by the U. S. Bureau of Statistics.

2.5 COST-RELATED DEFINITIONS

The terminology used in this study is that practiced by the McDonnell Douglas Corporation. In order to assist users of the report who are familiar with different terms or groupings of cost-related activities, the following definitions are presented:

1. Engineering Design - involves the design and analysis of individual components and assemblies in the life support system.
2. Program Management - relates to planning, organizing, directing and controlling the project. Includes scheduling deliveries, coordinating changes and monitoring problem areas.
3. System Engineering - involves system design as opposed to component or assembly design. Includes design, analysis design support, and total system non-separable hardware design and integration effort.
4. Development Testing - involves testing with breadboard and prototype hardware that is required to evaluate component and assembly design concepts and performance.

TABLE II - REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN

NON-RECURRING	%	RECURRING	%
Design	16.68	Flight Hardware Production	54.56
Subcontractor General & Administrative	8.62	Subcontractor G&A	9.22
Subcontractor Fee	3.62	Subcontractor Fee	3.88
Program Management	1.24	Program Management	1.36
System Engineering	5.25	Sustaining Engineering	1.96
Development Test	3.44		
Qualification Test	2.54		
Reliability Test	4.09		
AGE	18.45		
Tooling	3.87	Sustaining Tooling	1.69
Non-accountable Test Hardware	1.67		
Specifications, Vendor Coordination and Procurement Expenses	13.62	Specifications, Vendor Coordination and Procurement Expenses	15.49
System Integration	8.36	System Integration	7.15
Prime's Testing	8.17	Minor Subcontracts	4.69
Minor Subcontracts	0.38		
TOTAL	100 %		100 %

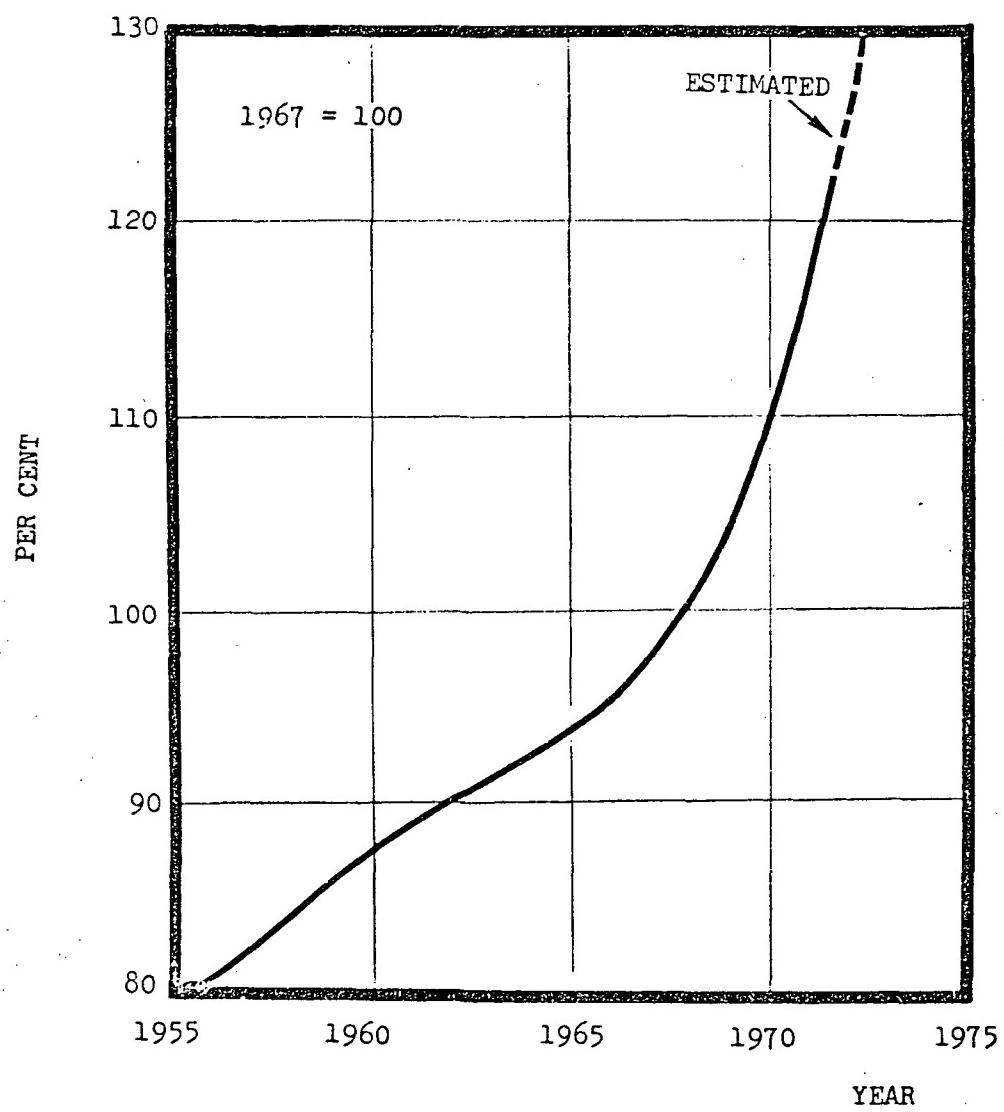


FIGURE 1 - Consumer Price Index
(Source: U. S. Bureau of Labor Statistics)

5. Qualification Testing - deals with formal qualification testing to ensure that components and assemblies provided meet mission performance and design requirements.
6. Reliability Testing - includes component and assembly life cycle and failure analysis testing to ensure operation of the system for the required mission duration.
7. Tooling - involves the design, fabrication and maintenance of component and assembly tools.
8. Non-Accountable Test Hardware - includes prototype units, breadboards, operational mock-ups and other non-deliverable development hardware items.
9. Aerospace Ground Support - includes design and fabrication of system test and servicing, system handling and checkout and hardware necessary during acceptance testing and launch operations.
10. Sustaining Engineering - includes incorporation of changes, modifications to design and contractor's project engineering design.
11. Subcontractor General and Administrative - includes overhead expenses charged as fixed percentages of all other costs.
12. Subcontractor Fee - involves the fee charged by the subcontractor as negotiated at beginning of the contract.
13. Minor Subcontractor - includes procurement costs for minor valves, lines and other required miscellaneous parts.
14. Prime Contractor Costs - include specifications, vendor coordination, procurement and documentation expenses.
15. Recurring Costs - recurring expenditures are divided into the Prime Contractor and Major Subcontractor costs. The Prime Contractor efforts involve primarily the incorporation of the life support systems into the spacecraft. The Major Subcontractor costs are broken into Sustaining Engineering, Tooling and System Production. The System Production expenditures are segregated into subsystems and these are in turn segregated into components.

16. Non-recurring - non-recurring expenditures for each life support subsystem are segregated into Prime Contractor and Major Subcontractor efforts. The Prime Contractor effort involves specification, coordination and integration of the system into the spacecraft. The Major Subcontractor effort is divided into Design and Development, AGE, Program Management and System Engineering, Test Operations and Hardware. The Design and Development costs are segregated into major subsystems.

SECTION 3

COST ESTIMATES OF OXYGEN RECOVERY SYSTEMS

Oxygen may be recovered from exhaled carbon dioxide by a number of physico-chemical processes by the reduction of CO₂ to carbon or methane and water, followed by the electrolysis of water to metabolic oxygen and hydrogen. Direct conversion of CO₂ to carbon and oxygen has also been under investigation. However, solid electrolyte which is the leading direct conversion process has not been yet proven operationally feasible and thus will not be discussed in this report. Oxygen recovery processes considered are the following:

1. Sabatier CO₂ reduction
2. Bosch CO₂ reduction
3. Solid polymer electrolyte water electrolysis
4. Circulating KOH electrolyte water electrolysis

Either one of the CO₂ reduction processes may be combined with one of the two water electrolysis methods to attain oxygen recovery from CO₂. The Sabatier process has been operated successfully in two consecutive manned simulator tests of sixty and ninety days in duration. The methane produced in the Sabatier process leads to the loss of large amounts of hydrogen, when it is vented overboard. The Bosch process, by contrast, produces solid carbon and water and requires no hydrogen make-up for continuous operation. An operational drawback to the Bosch process is the deposition of solid carbon on the reactor. This problem has been partially alleviated by the use of expendable cartridges containing the required catalyst. The Bosch process has been bench-tested, but has not undergone any extended tests as a part of integrated manned life support systems to prove its operational feasibility.

Of the two water electrolysis methods, only the KOH electrolyte subsystem has undergone integrated manned testing. The SPE process has been life-tested and currently appears to be more promising in performance and less troublesome in operation than processes utilizing KOH electrolyte. Oxygen recovery system criteria for the four systems considered are presented in Tables III and IV which also present the relative characteristics, operational differences and status of each of the four subsystems.

TABLE III - COMPARISON OF CARBON DIOXIDE REDUCTION SUBSYSTEMS

SUBSYSTEM CHARACTERISTICS	SABATIER CO ₂ REDUCTION SUBSYSTEM	BOSCH CO ₂ REDUCTION SUBSYSTEM
Crew Size	6 Men	6 Men
CO ₂ Processed, Average	2.2 lbs./Man-day	2.2 lbs./Man-day
CO ₂ Delivery Purity	98%	99%
Reactor Operating Pressure	30 to 40 Psia	15 Psia
Condenser Coolant	Water	Water
Coolant Inlet Temperature	50°F	40°F
Water Produced	5.4 lb/day	10.8 lb/day
System Operation	1. CO ₂ and hydrogen react over Ni or Ru catalyst at 500-700°F to produce CH ₄ and H ₂ O. 2. Water separated in a Water/Gas separator and routed to electrolysis unit. 3. H ₂ from electrolysis returned to reactor.	1. CO ₂ and H ₂ react over expendable iron catalyst at 1200°F to produce carbon and water. 2. Water separated and routed to electrolysis unit. 3. H ₂ from electrolysis returned to reactor.
System Status/Availability	1. Low-Fidelity prototypes developed and successfully operated in NASA 60 and 90-day tests. 2. Low temperature catalysts developed by Wright-Patterson AFB.	1. Units developed utilizing both rotating and expendable cartridge catalysts. 2. Integrated system test to prove operational feasibility required.
Operational Problems	1. Reactor temperature control 2. CO ₂ purity	1. Carbon deposition 2. CO ₂ purity

TABLE IV - COMPARISON OF WATER ELECTROLYSIS SUBSYSTEMS

SUBSYSTEM CHARACTERISTICS	SPE ELECTROLYTE SUBSYSTEM	CIRCULATING KOH ELECTROLYTE SUBSYSTEM
Crew Size	6 Men	6 Men
O ₂ Requirement	14.0 Lbs./Day	14.0 Lbs./Day
H ₂ Supply Rate	1.57 Lbs./Day	1.56 Lbs./Day
O ₂ Outlet Pressure Range	0. to 14.7 Psia	21 to 27 Psig
H ₂ Outlet Pressure Range	0 to 40 Psia	9 Psig
Coolant	Water	Water
Coolant Flow Rate	60 Lbs./Hr	0.5 GPM
Feed Water Inlet Temperature	50 to 160°F	50 to 160°F
System Operation	1. Electrolyte is ion exchange plastic sheets. 2. Water fed to cathode side only 3. System operated normally at 200 ASF, may operate up to 1000 ASF and 700 psig discharge gas.	1. Electrolyte is 35% KOH in water, held in asbestos matrix between electrodes. 2. Electrolyte circulated thru matrix and cooled by external heat exchanger
System Status/Availability	1. One-man module bench-tested for 1500 hours. 2. Six-man prototype under development	1. A 4-Man subsystem developed and tested in NASA 90-day test and in 180-day life-test. 2. Subsystem requires life testing and integrated manned life support system testing
Operational Problems	Subsystem requires additional development and repackaging	

A discussion of each of the four oxygen recovery systems and detailed cost estimates of the processes involved are presented in the following paragraphs.

3.1 SABATIER CARBON DIOXIDE REDUCTION SYSTEM

Process Description:

The Sabatier process involves the hydrogenation of CO_2 over a 400 to 700°F catalyst in a reactor. The Sabatier reaction is summarized by the following equation:



The Sabatier water product is electrolyzed to oxygen, for breathing, and to hydrogen for return to the Sabatier reactor.

The primary components of the Sabatier reactor include a CO_2 pressure regulator, H_2 and CO_2 mixture control valves, a catalytic reactor bed, a reactor pressure control valve, and a zero-g condenser/water separator. An electric heater also is provided in the Sabatier cooling air inlet line for reactor startup operations only. A schematic of the unit is presented in Figure 2.

The Sabatier reactor obtains CO_2 at an accumulator pressure of 30 to 40 psia. The CO_2 flows through the pressure regulator, which obtains a pressure reference from the H_2 supply. The regulated CO_2 then flows through a control valve under critical flow conditions. The H_2 flows directly to a separate critical flow-control valve. The two gas streams mix downstream of the control valves and then flow into the reactor. The reactor is a jacketed cylinder; the inner cavity contains the catalyst. Nickel-on-Kiesleguhr has been used as a catalyst, usually operated at 700°F. Other catalysts have also been investigated. The most promising are the noble metals such as ruthenium, which operates in the 450 to 600°F range, and rhodium.

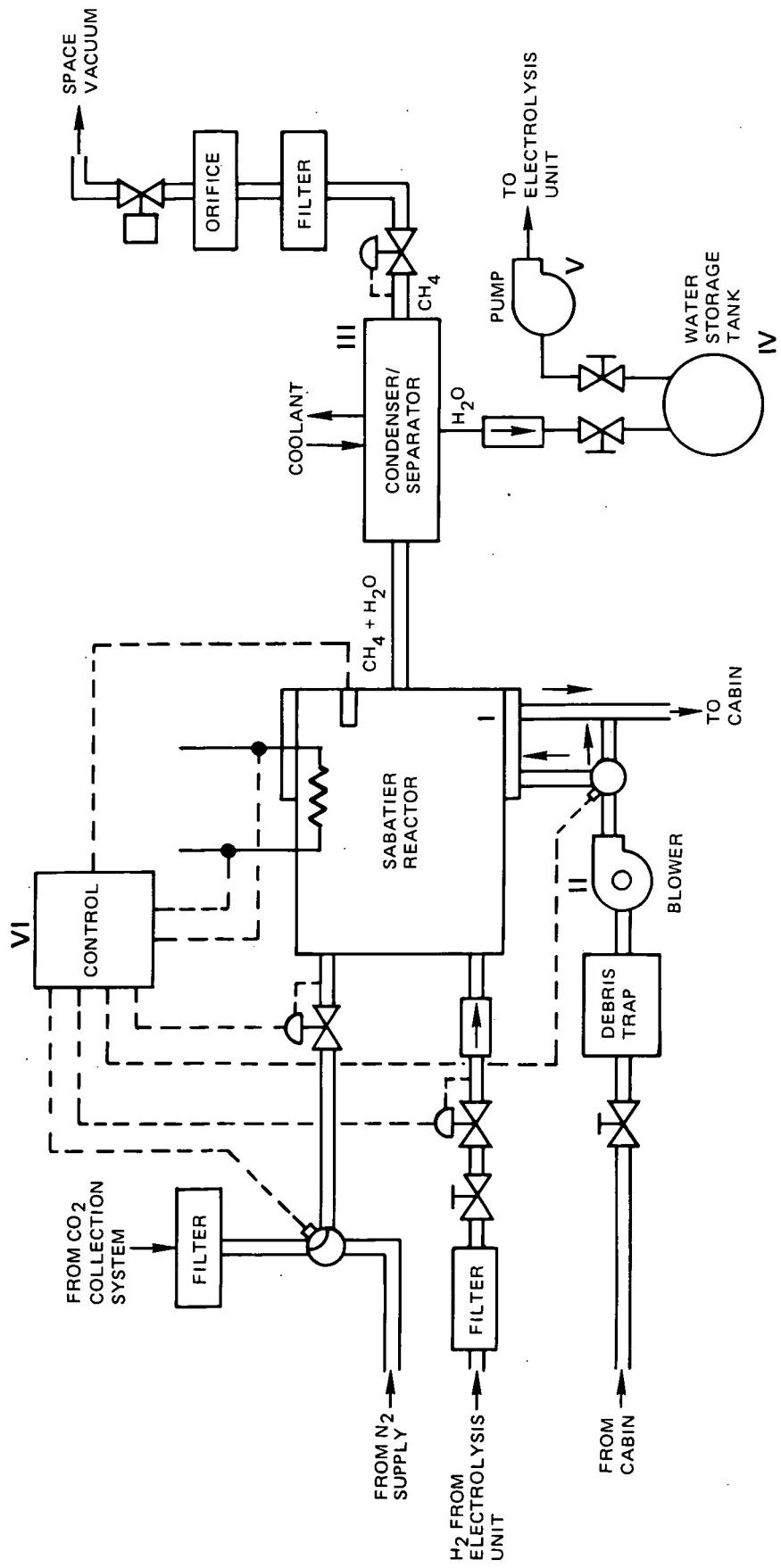


Figure 2. Sabatier CO₂ Reduction System

Cooling air flows through the outer jacket of the reactor to remove process heat. The catalyst bed is normally operated at a pressure ranging from 710 to 750 mmHg and a temperature of 500 to 700°F. The H₂/CO₂ mixture reacts to form methane and steam. The stoichiometric ratio is 4:1 by volume but operation at a ratio of 2.5:1 has been used since it normally eliminates the need of supplying additional hydrogen to the system.

The product gases containing some excess CO₂ and a small amount of unreacted H₂ leave the reactor and flow through the zero-g condenser/sePARATOR where the steam is condensed and separated as water. The CH₄ and unreacted gases then flow through the critical-flow reactor pressure-control valve to space vacuum. The zero-g condenser/sePARATOR is approximately 8 in. long by 4 in. wide by 1-1/2 in. high and is divided into two compartments by a partition of porous metal. Water, cooled by an integral circuit, wets one surface of the porous plate. The reaction gases flowing along the opposite surface are cooled and the stream condenses and wets the porous surface. The condensed water is then transferred through the porous plate into the cooling water by capillary action and a controlled pressure difference. Product water flowing through the plate increase the displacement of a negative-pressure device. When fully displaced, a reed switch is magnetically tripped, which introduces compressed CO₂ to displace the water into the water storage tank. The backup condenser collects any water it recovers in a small accumulator. A switch in the accumulator activates a positive displacement pump which also discharges the condensate into the water storage tank.

A listing of the components of the Sabatier CO₂ reduction system, including component weights and spares, is given in Table V.

System Performance and Characteristics:

The physical, performance and interface characteristics of the Sabatier CO₂ reduction system are as follows:

TABLE V - SABATIER CO₂ REDUCTION SYSTEM COMPONENTS LIST

COMPONENTS	QUANTITY	SPARES	UNIT WEIGHT (LBS.)
Valve, 3-Way Electrical, Man. Over	2	1	1.5
Valve, Shut-off, Gas	2	1	1.0
Valve, Vacuum, Shut-off Electrical, Man. Over.	1	1	3.0
Valve, Shut-off, Liquid	2	1	0.8
Pressure Regulator	3	2	1.5
Valve, Check, Gas	1	1	0.7
Valve, Check, Liquid	1	1	0.5
Filter, Debris	4	4	2.0
Heat Exchanger, Condenser	1	0	4.0
Separator, Sabatier H ₂ O	1	1	6.0
Sensor Temperature, Sabatier Reactor	1	2	0.3
Controller, Sabatier Reactor	1	1	6.0
Reactor, Sabatier	1	1	36.0
Blower, Cooling Air	1	1	2.0
Pump Sabatier Condensate	1	1	2.5
Tank, Water Storage	1	1	40.0

Crew Size	= 6 Men
CO ₂ Produced, Average	= 2.2 Lbs/Man-Day
CO ₂ Produced, Maximum	= 3.11 Lbs/Man-Day
CO ₂ Delivery Purity	= 98%
CO ₂ Delivery Pressure to Sabatier System	= 30 - 40 PSIA

Performance Characteristics of the system's major components are as follows:

1. Sabatier Reactor

H ₂ Feedrate (max lb/hr)	0.136
CO ₂ Feedrate (max lb/hr)	1.3
H ₂ Conversion Efficiency	0.98
Reactor Temperature (°F)	
maximum	700
minimum	450
Startup Heater Power (watts dc unregulated)	150
Catalyst Material	0.5% Ru or Nickel on Alumina
Catalyst Weight (lbs)	15.0
Maximum Operating Pressure (psia)	50
Nominal Operating Pressure (psia)	14
Coolant Air Mass Flowrate (lbs/hr)	60

2. Sabatier Condenser

	<u>Cont</u>	<u>Cycle</u>
Product Gas Flowrate (lb/hr) Nominal	0.63	1.08
Maximum	0.83	1.44
Q Sensible (Btu/hr)	117	200
Q Latent (Btu/hr)	351	604
Gas Outlet Dewpoint (°F)	55	
Gas Side ΔP (in of H ₂ O)	2.0	
Coolant Inlet Temperature (°F)	50	
Coolant Flowrate (lb/hr)	150	
Coolant Side ΔP (psid)	0.1	

3. Water Separator

Water Flow (max lb/hr)	0.604
Water Removal Efficiency	100%
Maximum Operating Pressure (psia)	50
Nominal Operating Pressure (psia)	14.7

The Sabatier CO₂ reduction system has the following power requirements:

Continuous Power (including cooling air blower), A. C.	85 watts
Heater Start-up Power, D. C., unregulated	150 watts
System's Total Weight	80 Lbs
System's Volume	3 ft ³

Cost Estimating Relationships:

The Sabatier CO₂ reduction system components have been grouped in six groups, designated as I through VI, as shown in the system schematic, Figure 2. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's:

1. Sabatier Reactor:

The CER for the Sabatier reactor is given as follows:

$$\text{Sabatier Reactor Assembly Fabrication Cost } C = 159 W^{0.267} N_p^{1.905} + 3900 W_{oc} \text{ dollars}$$

where,

W = Sabatier Reactor Weight = 36 lbs

N_p = Number of ports in reactor = 5, and

W_{oc} = Weight of associated components = 9.7 lbs

Substituting the values of variables in the CER yields:

$$C = 155 \times 2.608 \times 21.5 + 3900 \times 9.7 = 46,518 \text{ dollars}$$

2. Cooling Air Blower:

The CER for the cooling air blower fabrication cost is given by $C = 38.2P^{0.942} + 2192 W_{oc}$ dollars where,

P = electrical power input to the air blower = 50 watts, and
 W_{oc} = other components weight = 4.0 lbs.

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 40 + 2192 \times 4 = 10,296 \text{ dollars}$$

3. Condenser and Water Separator:

The following CER is used to evaluate the condenser heat exchanger and separator fabrication costs:

$$C = 159 w^{0.267} N_p^{1.905} + 2959 W_{oc} \text{ dollars}$$

where

w = condenser heat exchanger weight = 4.0 lbs
 N_p = number of ports per heat exchanger = 4, and
 W_{oc} = weight of other components = 7 lbs

Subsitueting the values of the variable in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 7 = 23,952 \text{ dollars}$$

4. Water Storage Tank:

The CER for the Sabatier water storage tank is given as follows:

$$\text{Tank fabrication cost } C = 1,918 V^{0.267} + 2959 W_{oc} \text{ dollars}$$

where,

V = volume of tank = 1.0 ft^3 , and

W_{oc} = weight of associated equipment = 1.5 lbs.

Substituting the above values in the tank's fabrication cost equations results in the following:

$$C = 1918 + 2959 \times 1.5 = 6357 \text{ dollars}$$

5. Water Transfer Pump:

The CER for the water transfer pump is given by the following relation:

$$\text{Pump fabrication cost } C = 91 P_w^{0.942} + 670 W_{oc} \text{ dollars}$$

where,

P_w = water transfer pump power input = 20 watts, and

W_{oc} = other components weight = 1.0 lb

Substituting the values of the variables in the above CER yields the following:

$$C = 91 \times 16.8 + 670 = 2199 \text{ dollars}$$

6. Controller

The CER used for the controller fabrication cost was based on CER's developed for similar equipment and is given as follows:

$$\text{Controller fabrication cost } C = 4795 W \text{ dollars}$$

where,

W = controller weight = 6.0 lbs

thus,

$$C = 4795 \times 6 = 28,770 \text{ dollars}$$

Integrated Sabatier CO₂ Reduction System's Recurring CER:

The integration costs of components and assemblies into the Sabatier CO₂ reduction system are obtained by utilizing the system's recurring CER as defined in previous sections of this report. Applying the said CER, then:

$$\begin{aligned} \text{First unit cost } C_F &= 1.833 \times 1.1 \times (46,518 + 10,296 + 23,952 + 6357 + 2199 \\ &\quad + 28,770) = 2.016 \times 118,092 = 238,073 \text{ dollars} \end{aligned}$$

and assuming the production of two flight-type units, one for flight and the other for back-up, then the total hardware cost is given by:

$$C_T = 238,073 \times (2)^{1-0.1047} = 441,625 \text{ dollars}$$

Integrated Sabatier CO₂ Reduction System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on typical cost breakdown ratios presented in Table II, which are based on actual cost data collected in a space vehicle hardware production program. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation:

$$\text{System design cost } C = 34,935N + 102,942 \text{ dollars}$$

The Sabatier CO₂ reduction system comprises 16 component types as shown in Table V. Accordingly, system design cost $C = 558,960 + 102,942 = 661,902$ dollars. Values of other non-recurring cost items are listed in Table VI, which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

3.2 BOSCH CARBON DIOXIDE REDUCTION SYSTEM

Process Description:

The Bosch reaction is summarized by the following equation:

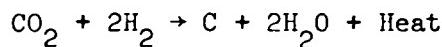


TABLE VI - SABATIER CO₂ REDUCTION SYSTEM COST BREAKDOWN

Non Recurring		Recurring	
System Engineering Design	661,902	Flight Hardware Production (2 units)	240,951
Subcontractor General and Administrative	342,203	Subcontractor G&A	40,718
Subcontractor Fee	143,633	Subcontractor Fee	17,135
Program Management	49,643	Program Management	6,006
System Engineering	208,499	Sustaining Engineering	8,656
Development Test	136,352		
Qualification Test	100,609		
Reliability Test	162,166		
AGE	732,063		
Tooling	153,561	Sustaining Tooling	7,463
Non-accountable Test Hardware	66,190		
Specifications, Vendor Coordination and Procurement Expense	540,774	Specifications, Vendor Coordination and Procurement Expense	68,408
System Integration	331,613	System Integration	31,576
Prime's Testing	324,332		
Minor Subcontracts	15,224	Minor Subcontracts	20,712
Total	3,968,764		441,625

Total Sabatier CO₂ Reduction System Cost = 3,968,764 + 441,625
= 4,410,389 Dollars

The reaction occurs in the presence of an iron catalyst at temperatures of 1100 to 1800°F. The reaction results in a partial conversion, ranging from 30% at the lower temperatures up to 98% at the higher temperatures. Bosch reactors are usually operated at temperatures between 1100 and 1300°F, where maximum formation of carbon occurs. The reaction gases are recycled to achieve a higher degree of conversion. The reaction rate is controlled by many apparently independent, but nonetheless interrelated variables. The most important variables relate to the conditions in the reactor. These variables may be grouped as the catalyst, the gas stream composition and the reaction kinetics. Reaction kinetics include the effect of reactor temperature and the gas flow rate or recycle rate through the reaction loop as controlled by the recycle compressor. Increasing the flow rate through the reactor increases the probable number of collisions per unit time, thereby increasing the reaction rate, and this in turn calls for higher compressor power requirements.

Conversion rates were found to be somewhat insensitive to reactant gas H₂ to CO₂ volume ratio, but were more favorable when a hydrogen-rich ratio was employed. Two types of Bosch units have been used in practice. The first utilizes expendable cartridge catalysts. The other type employs a nonexpendable rotating catalyst. A schematic diagram of a Bosch CO₂ Reducer with an expendable cartridge catalyst is shown in Figure 3. A compressor is used to circulate carbon dioxide, makeup hydrogen, and recycle gases through the system. The gases are heated in a regenerative heat exchanger by the hot exit gases from the reactor before entering the reactor. The reactor is basically a canister with startup strap heaters wound around its external circumference. The expendable cartridge is a screen mesh cylinder filled with the steel wool catalyst and placed inside the reactor housing. A filter is placed downstream of the reactor to trap solid carbon or other particles. The resultant water is condensed in the condenser/H₂O separator, collected, and piped to the water electrolysis unit.

A listing of the components of the Bosch CO₂ reduction system including component weights and spares, is given in Table VII.

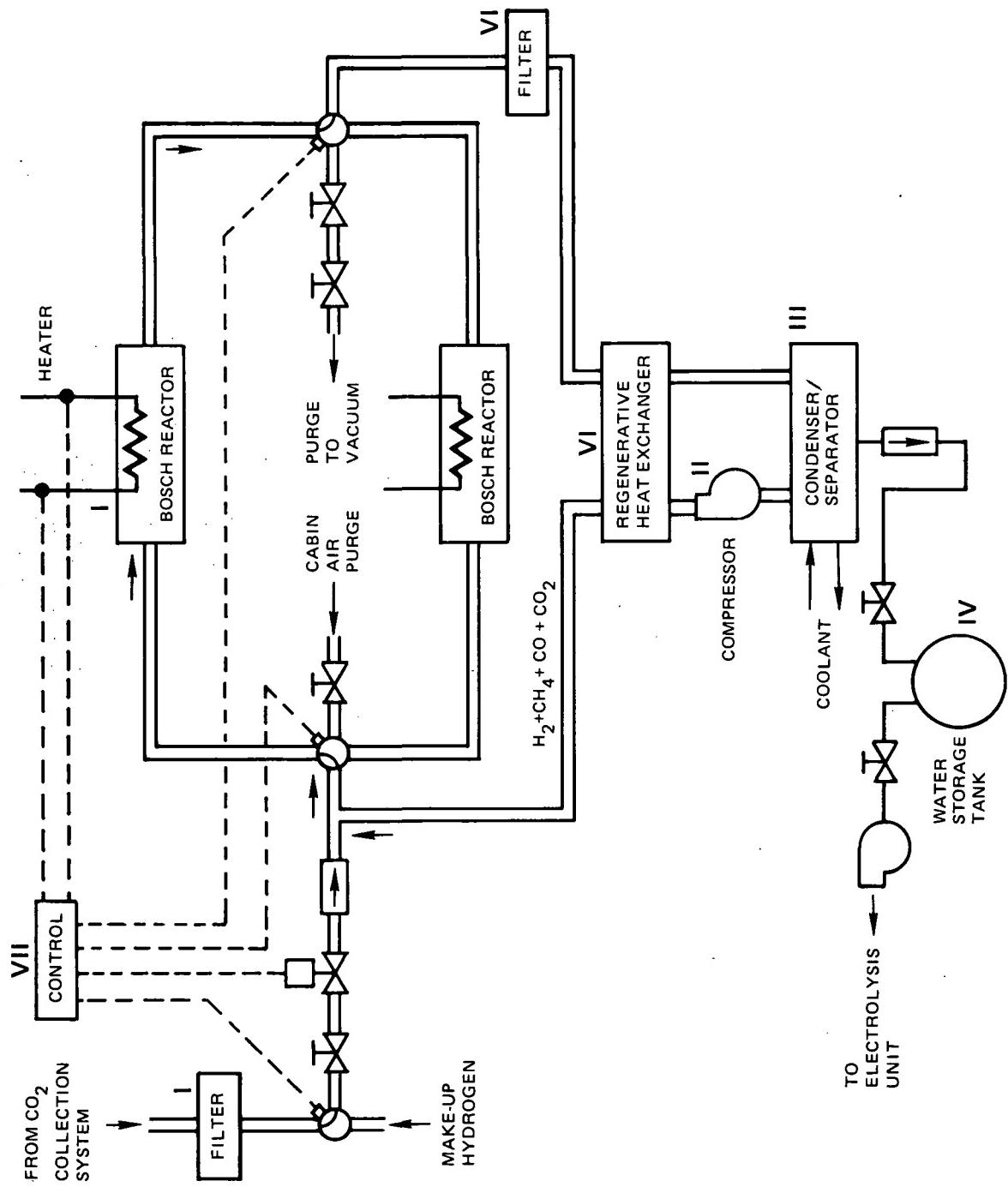


Figure 3. Bosch CO₂ Reduction System

TABLE VII BOSCH CO₂ REDUCTION SYSTEM COMPONENTS LIST

COMPONENT	QUANTITY	SPARES	UNIT WEIGHT (LBS.)
Valve, 3-Way Electrical Man. Over	1	1	2.5
Valve, 4-Way Electrical, Man. Over	2	1	2.5
Valve, Shut-off, Gas	3	2	1.0
Valve, Vacuum, Shut-off, Electrical, Man. Over.	1	1	3.0
Valve, Shut-off, Liquid	2	1	0.8
Valve, Shut-off, Elect., Man. Over	1	1	2.0
Valve, Check, Gas	1	1	0.7
Valve, Check, Liquid	1	1	0.5
Tank, water storage	1	1	40.0
Filter, Debris	2	2	2.0
Heat Exchanger, Regenerative	1	0	10.0
Heat Exchanger Condenser	1	0	4.0
Separator, Water	1	1	6.0
Controller, Bosch Reactor	1	1	6.0
Reactor, Bosch	1	1	25.0
Compressor, Recycle Gases	1	1	2.0
Pump, Condensate	1	1	2.5

System Performance and Characteristics:

The physical, performance and interface characteristics of the Bosch CO₂ Reduction System are as follows:

Capacity, number of men	6
CO ₂ rate, lb/man-day, average	2.2
Feed gas impurities, maximum % by volume	1.0
Feed gas pressure range, psig	5 to 10
Recycle flow rate lb/day	144
Catalyst cartridge replacement interval, days	3
Condenser coolant	Water
Coolant inlet temperature, °F	40
Coolant flow, lb/hr	90
Ambient temperature, °F	75
Ambient pressure, psia	14.7
Reduction unit pressures, psia	> 14.7
Maximum reactor pressure, psig	15.0
Dry recycle gas composition, % by volume	
H ₂	40
CH ₄	30
CO	20
CO ₂	10
Water production rate, lbs/day	10.8
Hydrogen flow rate, lbs/day	1.2
Carbon Production rate lbs/day	3.6
System's power requirement:	
Compressor, continuous, watts	450
Instrumentation, continuous, watts	20
Heater, start-up only, watts	500
Systems total weight, lbs.	120
System's volume, Ft ³	4.5

Cost Estimating Relationships:

Bosch CO₂ reduction system components have been grouped in seven groups, designated as I through VII, as shown in the system schematic, Figure 3. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's:

1. Bosch Reactor:

The CER for the Bosch reactor was assumed to be similar to that used for the Sabatier reactor and is given as follows:

Bosch reactor assembly fabrication cost C

$$= 159 W_p^{0.267} N_p^{1.905} Q^{0.89} + 3900 W_{oc} \quad \text{dollars}$$

where,

$$W = \text{Sabatier Reactor Weight} \quad = 25 \text{ lbs.,}$$

$$N_p = \text{Equivalent number of ports in reactor} \quad = 2$$

$$Q = \text{Number of reactors} \quad = 2, \text{ and}$$

$$W_{oc} = \text{Weight of Associated Components} \quad = 11.7 \text{ lbs}$$

Note that the reactor has only one port, but due to its complexity, it was assumed to be equivalent to 2 ports. Substituting the values of variables in the CER yields:

$$C = 155 \times 2.366 \times 3.93 \times 1.855 + 3900 \times 11.7 = 48,304 \text{ dollars}$$

2. Recycle Gases Compressor:

The recycle gases compressor CER is given by the following:

$$\text{Compressor Fabrication Cost } C = 38.2 P^{0.942} \text{ dollars,}$$

where,

P = electrical power input to the compressor = 200 watts, and

Substituting the value of the variable P in the CER yields: $C = 5654$ dollars

3. Condenser/Separator

The CER for the condenser/separator utilizes the heat exchanger relation for the condenser and assumes the separator to be part of the associated components, w_{OC} . The condenser/separator fabrication cost equation is given as follows:

$$C = 159W_p^{0.267}N_p^{1.905} + 2959 w_{OC} \text{ dollars}$$

where,

W_p = Condenser heat exchanger weight = 4.0 lbs.

N_p = number of ports per heat exchanger = 4, and

w_{OC} = weight of other components = 0.5 lbs.

Substituting the values of the variable in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 0.5 = 4,719 \text{ dollars}$$

4. Water Storage Tank:

The CER for the condensate water storage tank is given as follows:

$$\text{Tank fabrication cost } C = 1,918 V^{0.267} + 2959 w_{OC} \text{ dollars}$$

where,

V = volume of tank = 1.0 FT³, and

w_{OC} = weight of associated equipment = 1.0 lbs.

Substituting the above values in the tank's fabrication cost equations result in the following:

$$C = 1918 + 2959 \times 1.0 = 4877 \text{ dollars}$$

5. Water Transfer Pump:

The CER for the water transfer pump is given by the following relation:

$$\text{Pump fabrication cost } C = 91 P_w^{0.942} + 670 W_{OC} \quad \text{dollars}$$

where,

P_w = water transfer pump power input = 20 watts and

W_{OC} = other components weight = 1.0 lb.

Substituting the values of the variables in the above CER yields the following:

$$C = 91 \times 16.8 + 670 = 2199 \quad \text{dollars}$$

6. Regenerative Heat Exchanger:

The recycle g a s loop regenerative heat exchanger CER is given by the following:

$$\text{Heat exchanger fabrication cost } C = 159 W^{0.267} N_p 1.905 + 2959 W_{OC} \quad \text{dollars}$$

where,

W = heat exchanger weight = 10.0 lbs,

N_p = number of ports per heat exchanger = 4,

W_{OC} = weight of other components = 8.5 lbs

Substituting the values of the variable in the CER yields:

$$C = 159 \times 1.85 \times 14.05 + 2959 \times 8.5 = 29,285$$

7. Controller

The CER used for the controller fabrication cost was based on CER's developed for similar equipment and is given as follows:

$$\text{Controller fabrication cost } C = 4795 W \quad \text{dollars}$$

where,

W = controller weight = 6.0 lbs

thus,

$$C = 4795 \times 6 = 28,770 \quad \text{dollars}$$

Integrated Bosch System's Recurring CER:

The integration costs of components and assemblies into the Bosch CO₂ reduction

system are obtained by utilizing the system's recurring CER as defined in previous sections of this report. Applying the said CER, then:

$$\begin{aligned} \text{First unit cost } C_F &= 1.833 \times 1.1 \times (48,304 + 5,654 + 4,719 + 4,877 \\ &\quad + 2,199 + 29,285 + 28,770) \\ &= 2.0163 \times 123,808 = 249,634 \quad \text{dollars} \end{aligned}$$

and assuming the production of two flight-type units, one for flight and the other back-up, then the total hardware cost is given by:

$$C_T = 249,634 \times (2)^{1-0.1047} = 463,071 \quad \text{dollars}$$

Integrated Bosch CO₂ Reduction System's Non Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on typical cost breakdown ratios presented in Table II, which are based on actual cost data collected in a space vehicle hardware production program. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation:

$$\text{System design cost } C = 34,935N + 102,942 \quad \text{dollars}$$

The Bosch CO₂ Reduction System comprises 17 component types as shown in Table VII.

Accordingly, system design cost $C = 593,895 + 102,942 = 696,837 \quad \text{dollars}$

Values of other non-recurring cost items are listed in Table VIII, which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

3.3 SOLID POLYMER ELECTROLYTE (SPE) ELECTROLYSIS SYSTEM:

The SPE electrolysis system comprises the electrolysis modules, pumps deionizer columns, filters, heat exchangers gas/liquid separators pressure regulators, valves and associated components. A schematic of the SPE electrolysis system is shown in Figure 4. The system operation is as follows: The make-up water is mixed with the recycled cooling water upstream of the water pump filters. The process water rate is fixed and pumped by the water metering pump. Downstream of the pump, the water flows through two process water deionizer resin beds which

TABLE VIII - BOSCH CO₂ REDUCTION SYSTEM COST BREAKDOWN

Non-Recurring	Recurring		
System Engineering Design	696,837	Flight Hardware Production (2 units)	252,651
Subcontractor General and Administrative	360,265	Subcontractor G&A	42,695
Subcontractor Fee	151,214	Subcontractor Fee	17,967
Program Management	52,263	Program Management	6,298
System Engineering	219,504	Sustaining Engineering	9,076
Development Test	143,548		
Qualification Test	105,919		
Reliability Test	170,725		
AGE	770,702		
Tooling	161,666	Sustaining Tooling	7,826
Non-accountable Test Hardware	69,684		
Specifications, Vendor Coordination and Procurement Expense	569,316	Specifications, Vendor Coordination and Procurement Expense	71,730
System Integration	349,115	System Integration	33,110
Prime's Testing	341,450		
Minor Subcontracts	16,027	Minor Subcontracts	21,718
Total	4,178,235		463,071

Total Bosch CO₂ Reduction System Cost = 4,178,235 + 463,071
= 4,641,306 dollars

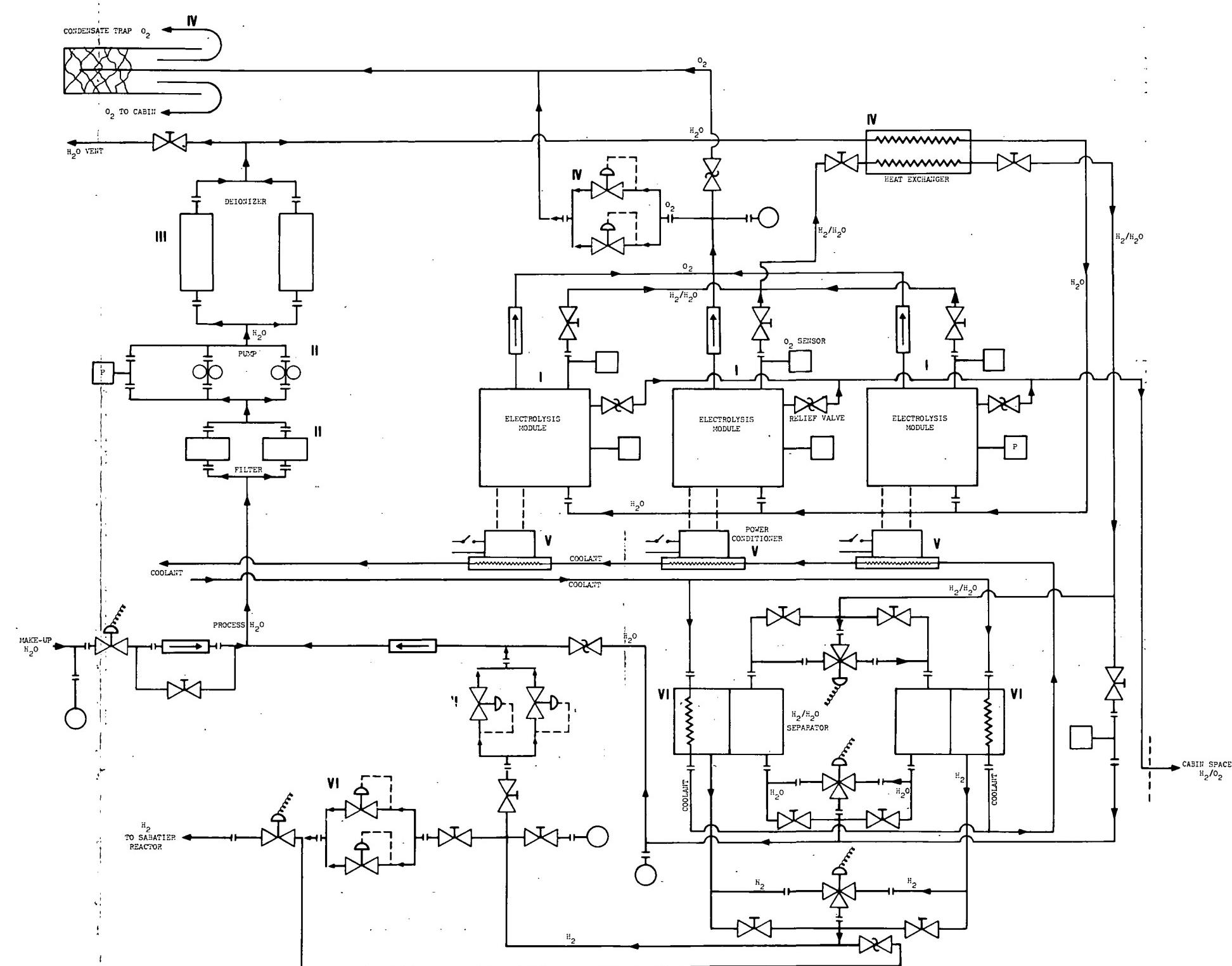


Figure 4. Solid Polymer Electrolyte Water Electrolysis Subsystem Schematic

reduces the contaminant level to acceptable system limits. The water then passes through a regenerative heat exchanger to increase the water temperature as it enters the electrolysis module for optimum system performance. Each module is packaged within a container which is isolated from space vacuum by the container pressure relief valve.

Since the electrolysis mode of operation is by water feed to the cathode side only, water required for the anode side reaction diffuses through the cell electrolyte to generate oxygen at a rate determined by cell current. The generated oxygen thus contains only saturated water vapor at the temperature and pressure level of the oxygen exit side. The generated hydrogen contains the free liquid water required for module temperature control with this gas/water mixture subsequently passing through the normally-open manual module isolation valve. The oxygen sensor installed on the hydrogen discharge side senses the presence of oxygen in the hydrogen stream in the event of an internal cell leak and automatically removes power to the failed module. The hydrogen/water mixture passes through one side of the regenerative heat exchanger to transfer heat to the incoming process feed water. This mixture then enters into the H₂/H₂O phase separator. The exit water from the separator then passes to H₂/H₂O differential back-pressure regulators. The exit hydrogen from the separator similarly passes to a pair of H₂ absolute back-pressure regulators. The H₂/H₂O differential back-pressure regulators are referenced to the exit H₂ pressure.

No phase separation is required on the oxygen discharge side of the module due to expansion of the oxygen/water vapor mixture from a high module pressure of about 65 psia to the delivery cabin pressure of 5-14.7 psia. This lowers the dew point, resulting in no water condensation occurring in the oxygen discharge stream during normal operation. A condensate trap is installed on the system oxygen outlet to the cabin to collect any small amount of condensate accumulated during system shutdown or transients. Sustained operation then evaporates this residue. This water condensate is ultimately removed to the cabin environment by evaporation. The oxygen is delivered directly to the cabin through the O₂ absolute back-pressure regulator.

The spacecraft Liquid Heat Transport Loop provides water coolant to the hydrogen side phase separator and power conditioners for removal of most of the heat generated during the electrolysis cycle. The remainder of the heat is rejected to the cabin environment from the system package. No active temperature controls are required in the system throughout its operating range. A listing of the components of the SPE water electrolysis system, including component weights and spares, is given in Table IX.

System Performance and Characteristics:

The physical, performance and interface characteristics of the SPE electrolysis system are as follows:

Capacity, number of men	6
O ₂ Consumption rate, metabolic, Lbs/Man-day	2.0
O ₂ Leak rate, lbs/day	2.0
Cabin total pressure, psia	5.0 to 14.7
Cabin oxygen partial pressure, psia	3.1
Cabin nitrogen partial pressure	Diluent
Hydrogen supply rate, Lbs./day	1.56
Oxygen outlet pressure range, psia	0 to 14.7
Hydrogen outlet pressure range, psia	0 to 40
Maximum coolant inlet temperature, °F	50
Cabin temperature range, °F	63 to 77
Feed water inlet temperature range, °F	50 to 160
Cabin dewpoint range	46 to 60
Coolant medium	water
Coolant flow rate, Lbs/Hr	60
Input water electrolysis voltage range, VDC	40 to 60
Input instrumentation voltage range, VDC	25 to 31
Nominal input power (3 modules operating, including power conditioning), watts	1420
Instrumentation/control input power, watts	20
Maximum heat rejection to cabin air, BTU/Hr	125
Maximum Heat rejection to coolant loop, BTU/Hr	678
Installed system weight, Lbs.	140

TABLE IX - SPE ELECTROLYSIS SYSTEM COMPONENT LIST

COMPONENT	QUANTITY	SPARES	COMPONENT WEIGHT (LBS.)
Back-Pressure Regulator, ABS	4	4	2.50
Pressure Regulator, Differential	2	2	2.50
Valve, Solenoid, Gas	3	2	1.00
Valve, Solenoid, Liquid	2	1	1.00
Valve, ABS. Relief, Gas	4	1	1.50
Valve, ABS. Relief, Liquid	1	0	1.50
Valve, Check, Gas	4	8	0.70
Valve, Check, Liquid	1	2	0.50
Valve, Shut-off, Manual, Gas	7	3	0.75
Valve, shut-off, manual, liquid	2	1	0.75
Valve, manual vent, water	1	0	0.75
Electrolysis Module	3	2	16.50
Pump, Metering	2	2	2.25
Condenser/Separator	2	1	5.00
Filter, Water	2	10	1.50
Pressure Switch	3	1	0.60
Pressure Switch, Differential	2	4	0.60
Deionizer, Water	2	10	16.00
Valve, Quick Disconnect, Gas	30	3	0.50
Valve, Quick Disconnect, Liquid	38	5	0.50
Heat Exchanger	1	1	4.00
Power Conditioner	3	1	10.00
Coldplate	3	1	4.00
Condensate Trap	1	0	0.50
Oxygen Sensor	3	1	1.20
Control Electronics	1	1	3.00
Gage, Pressure Readout	4	4	0.25

Cost Estimating Relationships:

The SPE Electronics System components have been grouped in six groups, designated as I through VI, as shown in Figure 4. The recurring and non-recurring CER'S presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER'S developed and based on prior year dollar values.

Recurring CER'S:

1. Electrolysis modules

A study of the costs of similar electrochemical cells and of prototype water electrolysis cells indicates that the SPE electrolysis module fabrication cost may be given by the following relation:

$$C = (6250 W_M + 2192 W_{OC} + 2000) Q^{0.89} \text{ dollars}$$

where,

W_M = weight of module = 16.5 lbs.,

Q = number of modules = 3 , and

W_{OC} = weight of associated components = 7.0 lbs.

Substituting the values of the variables in the above CER yields the following:

$$\begin{aligned} C &= (2650 \times 16.5 + 2192 \times 7 + 2000) \times 2.66 \\ &= (103, 125 + 15, 344 + 2000) \times 2.66 = 324, 645 \text{ dollars} \end{aligned}$$

2. Pumps:

The CER for the water metering pump assembly is given by the following relation:

Condensate Pump and Condensate Loop Fabrication Cost C

$$= 91 P_W^{0.942} Q^{0.89} + 670 W_{OC} \text{ dollars}$$

where,

P_W = condensate pump power input = 20 watts,

Q = number of pumps = 2, and

W_{OC} = other components weight = 23.5 lbs

Substituting the values of the above variables in the pumps fabrication cost equation results in the following:

$$C = 91 \times 16.8 \times 1.855 + 670 \times 23.5 = 18,580 \text{ dollars}$$

3. Deionizers:

The CER utilized for the Deionizers is similar to that used for cost estimating multifiltration units and is given by the following:

$$\text{Deionizers fabrication cost } C = 200 W_D Q^{0.89} + 670 W_{OC} \text{ dollars}$$

where,

$$W_D = \text{deionizer weight} = 16 \text{ lbs.,}$$

$$Q = \text{number of deionizer units} = 2, \text{ and}$$

$$W_{OC} = \text{weight of associated components} = 2 \text{ lbs.}$$

Substituting the values of variables in the above CER yields:

$$C = 200 \times 16 \times 1.855 + 2 \times 670 = 7276 \text{ dollars}$$

4. Heat Exchanger:

The CER for H_2/H_2O to water vapor heat exchanger is given by the following:

$$\text{Heat exchanger assembly fabrication cost } C = 159 W^{0.267} N_p^{1.905} + 2959 W_{OC} \text{ dollars}$$

where,

$$W = \text{heat exchanger weight} = 4.0 \text{ lbs.,}$$

$$N_p = \text{number of ports per chiller} = 4, \text{ and}$$

$$W_{OC} = \text{weight of associated components} = 12.5 \text{ lbs}$$

Substituting the values of variables in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 12.5 = 40,227 \text{ dollars}$$

5. Power Conditioner/Coldplate Assembly:

The CER's for the power conditioner/coldplate assemblies include terms for both the power conditioner and the heat exchanger coldplate. The power conditioner/coldplate assembly fabrication cost is given by the following relation:

$$C = (14.9P^{0.942} + 1414 (W)^{0.267} N_p^{1.905}) \times Q^{0.89} \quad \text{dollars}$$

where,

P = power conditioner's power requirement = 1000 watts,

W = weight of coldplate = 4.00 lbs.,

N_p = number of ports per coldplate = 2, and,

Q = number of conditioner/coldplate assemblies = 3.

Substituting the values of variables in the above CER yields the following:

$$C = (14.9 \times 670 + 1414 \times 1.45 \times 3.72) \times 2.56 = 45,080 \text{ dollars}$$

6. Condenser/Separator Assembly:

The assembly contains hydrophilic porous glass tubes which pass water and hydrophobic teflon membranes which pass hydrogen, integrated with the heat exchanger which picks up the heat rejected from the hydrogen/water mixture.

The CER used for the fabrication cost of the condenser/hydrogen separator assembly is given as follows:

$$C = 159 W^{0.267} N_p^{1.905} Q^{0.89} + 2959 W_{oc} \quad \text{dollars}$$

where,

W = heat exchanger weight = 5.00 lbs.

N_p = number of ports per heat exchanger assembly = 5,

Q = number of heat exchanger assemblies = 2, and

W_{oc} = weight of associated components = 27.0 lbs.

Substituting the values of the variables in the above CER yields the following

$$C = 159 \times 1.54 \times 21.4 \times 1.855 + 2959 \times 27 = 89,610 \text{ dollars}$$

Integrated SPE Electrolysis System's Recurring CER:

The integration costs of components and assemblies into the SPE water electrolysis system are obtained by utilizing the system's recurring CER as defined in previous sections of the report. Applying the said CER, then

$$\begin{aligned} \text{First unit cost } C_F &= 1.833 \times 1.1 \times (324,645 + 18,580 + 7,276 \\ &\quad + 40,227 + 45,080) = 1,095,700 \text{ dollars} \end{aligned}$$

and assuming the production of two flight-type units, one for flight and the other for back-up, then the total hardware recurring cost is given by:

$$C_T = 1,095,700 \times (2)^{1-0.1047} = 2,032,500 \text{ dollars}$$

Integrated SPE Water Electrolysis System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on typical cost breakdown ratios presented in Table II, which are based on actual cost data collected in a space vehicle hardware production program. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

$$\text{System design cost } C = 34,935N + 102,942 \text{ dollars}$$

The SPE water electrolysis system comprises 27 component types as shown in Table IX. Accordingly, system design cost $C = 943,245 + 102,942 = 1,046,187 \text{ dollars}$.

Values of other non-recurring cost items are listed in Table X which also shows the breakdown of recurring cost items based on the production of two flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE X - SPE WATER ELECTROLYSIS SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	1,046,187	Flight Hardware Production (2 units)	1,108,932
Subcontractor General and Administrative	540,879	Subcontractor G&A	187,397
Subcontractor Fee	227,023	Subcontractor Fee	78,861
Program Management	78,464	Program Management	27,642
System Engineering	329,549	Sustaining Engineering	39,837
Development Test	215,515		
Qualification Test	159,020		
Reliability Test	256,316		
AGE	1,157,082		
Tooling	242,715	Sustaining Tooling	34,349
Non-accountable Test Hardware	104,619		
Specifications, Vendor Coordination and Procurement Expense	854,735	Specifications, Vendor Coordination and Procurement Expense	314,834
System Integration	524,140	System Integration	145,324
Prime's Testing	512,632		
Minor Subcontracts	24,062	Minor Subcontracts	95,324
Total	6,272,938		2,032,500

Total SPE water Electrolysis System Cost = 6,272,938 + 2,032,500
= 8,305,438 dollars

3.4 CIRCULATING KOH ELECTROLYTE WATER ELECTROLYSIS SYSTEM:

This type of electrolysis cells uses a potassium hydroxide electrolyte, as a solution of 35% KOH in water, which is contained in an asbestos matrix held between two electrodes. The alkaline electrolyte is circulated between the dual asbestos matrix of the cell and is cooled by a heat exchanger external to the cell. The circulation of the electrolyte helps to minimize concentration polarization and decrease the time required to reach steady-state operation after either starting up or adding make-up water to the electrolyte. A schematic of the circulating KOH electrolysis system is shown in Figure 5. The system comprises three electrolysis modules. Each contains 16 cells, connected hydraulically in parallel and divided electrically into two eight-cell banks. Cells within an eight-cell electrical bank are connected in series. Peripheral manifolding within the module provides separate paths for electrolyte circulation oxygen and hydrogen discharge, and nitrogen purge. By differential pressure control, the gas-liquid interface in the absorbent matrices contiguous to the electrodes is maintained to achieve phase separation. The electrolyte is pumped through a closed circulation loop by using one of two-in-line magnetic-coupled centrifugal pumps. The electrolyte leaving the pump passes through the tube side of a shell-and-tube heat exchanger. Coolant supplied to the shell side removes waste heat generated in the electrolysis modules. The electrolyte flow is split at a set of flowmeters into three paths leading to the electrolysis modules. Flow control valves in these lines are used to balance the flowmeters. Downstream of the electrolysis modules, the electrolyte is manifolded together and enters the electrolyte reservoir to be returned to the pump. Reference pressure is utilized from an external nitrogen pressure source controlled to the desired system pressure.

Water feed for the electrolysis process is supplied by direct injection into the reservoir. The proper water pressure and flow rate are effected by means of a gear pump, a manually adjustable flow control valve, and solenoid valve.

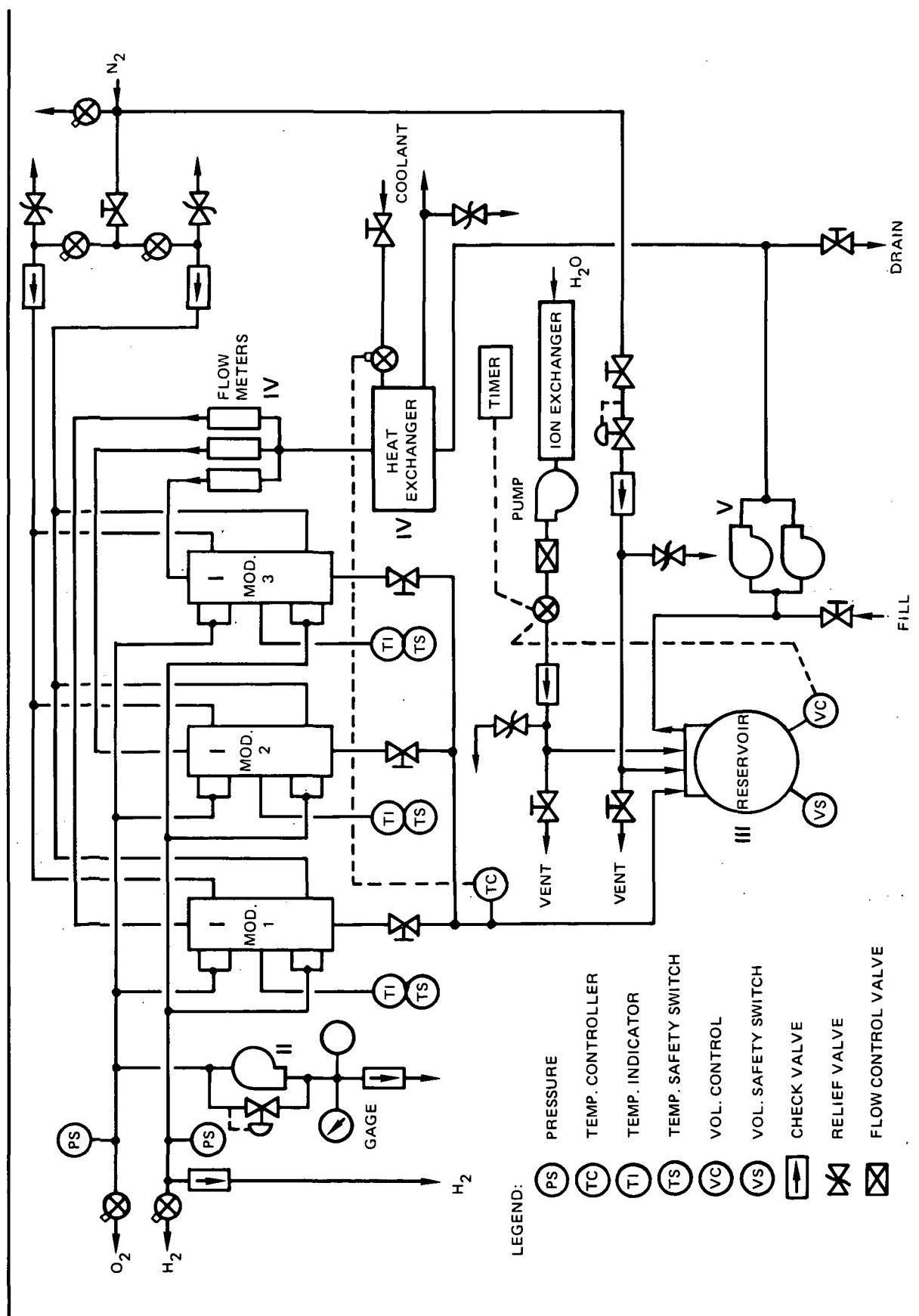


Figure 5. Circulating KOH Electrolyte Subsystem Schematic

Hydrogen is delivered from the electrolysis modules at approximately 9 psig. Oxygen discharged from the electrolysis modules at approximately 9 psig is pumped to 21-27 psig by means of a diaphragm pump. A pressure regulator across the pump maintains the pump suction pressure at 5 psig. Nitrogen purge is provided to maintain gas-liquid differential pressure during startup and interim shutdown. When this function is actuated, whether manually or automatically during safety shutdown, inlet and outlet solenoid valves in the hydrogen and oxygen discharge lines open, allowing nitrogen to flow through the oxygen and hydrogen chambers of the electrolysis modules. A micrometer valve is used to adjust the nitrogen flow rate. A listing of the components of the circulating KOH electrolysis system, including component weights and spares, is shown in Table XI.

System Performance and Characteristics:

The physical, performance and interface characteristics of the circulating KOH electrolysis system are as follows:

capacity, number of men	6
O ₂ Consumption rate, metabolic, lbs./man-day	2.0
O ₂ Leak rate, lbs./day	2.0
Cabin total pressure psia	5.0 to 14.7
Cabin oxygen partial pressure, psia	3.1
Cabin nitrogen partial pressure	Diluent
Nominal cell voltage	1.8 to 2.1
Hydrogen supply rate, lbs./day	1.56
Oxygen outlet pressure range, psia	21 to 27
Hydrogen outlet pressure range, psig	9
Maximum coolant temperature, °F	55
Cabin temperature range °F	63 to 77
Feed water inlet temperature range, °F	50 to 160
Cabin dewpoint range	46 to 60
Coolant medium	Water
Coolant flow rate, GPM	0.5

TABLE XI - CIRCULATING KOH ELECTROLYSIS SYSTEM COMPONENT LIST

COMPONENT	QUANTITY	SPARES	COMPONENT WEIGHT (LBS)
Electrolysis Module	3	3	15.00
Valve, Gas Manual	3	2	0.75
Valve, Gas, Solenoid	5	2	1.00
Valve, Relief, Gas	3	2	1.50
Valve, Relief, Liquid	2	1	1.50
Valve, Check, Gas	5	3	0.75
Pressure Regulator	2	2	2.50
Temperature Indicator	3	2	0.20
Temperature Safety Switch	3	2	0.50
Compressor	1	1	3.00
Pressure Switch	3	3	0.50
Gage	1	1	1.00
Reservoir	1	0	50.00
Volume Control	1	1	0.50
Temperature Control	1	1	0.50
Volume Safety Switch	1	1	0.50
Heat Exchanger	1	0	4.00
Flow Meter	3	2	1.00
Pump	3	2	2.50
Timer	1	1	6.00
Valve, Flow Control	1	1	1.00
Valve, Liquid, Manual	7	4	0.75
Valve, Liquid, Solenoid	2	1	1.00
Valve, Liquid, Check	1	1	0.50
Filter, Ion Exchange	1	1*	8.00

(*) NOTE: Plus replacements, as required

System Power Requirements:

45 ma 120/208 VAC, 400 Hz (3 sec. on, 15 min. off)

4.0 amp 115 vac, 1 phase, 60 Hz for controls and the oxygen compressor

1950 watts DC on high mode operation, continuous

670 watts DC on low mode operation, 2 hours/day

Installed System weight, lbs. 180

Cost Estimating Relationships:

The circulating KOH electrolysis system components have been grouped in five groups, designated as I through V, as shown in Figure 5. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior year dollar values.

Recurring CER'S:

1. Electrolysis modules:

A study of the costs of similar electrochemical cells and of prototype water electrolysis cells indicates that similar to the SPE electrolysis module, the circulating KOH electrolysis module fabrication cost may be given by the following relation:

$$C = (6250 W_M + 2000)Q^{0.89} + 2192 W_{OC} \quad \text{dollars}$$

where,

w_m = weight of module = 15 lbs.,

Q = number of modules = 3, and

W_{OC} = weight of associated components = 15.6 lbs.

Substituting the values of the variables in the above CER yields the following:

$$C = (6250 \times 15 + 2000) \times 2.66 + 2192 \times 15.6 = 288,890 \text{ dollars}$$

2. Compressor:

The CER utilized for oxygen supply compressor assembly is given by the following:

$$\text{Compressor assembly fabrication cost } C = 38.2 P_w^{0.942} + 2192 W_{oc} \text{ dollars}$$

where,

P_w = compressor power input = 35 watts, and

W_{oc} = other components weight = 8.5 lbs.

Substituting the values of variables in the above CER yields the following:

$$C = 38.2 \times 28.5 + 2192 \times 8.5 = 19,720 \text{ dollars}$$

3. Reservoir:

The CER utilized for the water reservoir is given as follows:

$$\text{Reservoir fabrication cost } C = 1918 V^{0.267} + 2959 W_{oc} \text{ dollars}$$

where,

V = tank volume = 1.0 ft³, and

W_{oc} = Weight of associated components = 1.0 lb.

Substituting the values of the variables in the above CER gives the following:

$$C = 1918 + 2959 = 4877 \text{ dollars}$$

4. Heat Exchanger:

The CER for the liquid-to-liquid heat exchanger water cooler is given by the following:

Heat exchanger fabrication cost C

$$= 159 W^{0.267} N_p^{1.905} + 2959 W_{oc} \text{ dollars}$$

where, W = heat exchanger weight = 4.0 lbs.,

N_p = number of ports per heat exchanger = 4,

W_{oc} = weight of other components = 6.25 lbs.

Substituting the values of the variable in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 6.25 \times 2959 = 21,733 \text{ dollars}$$

5. Pumps:

The CER for the two-water transfer pump assemblies, including the ion exchange filter and timer is given by the following relation:

Condensate Pump and condensate Loop Fabrication Cost C

$$= 91 P_W^{0.942} Q^{0.89} + 670 W_{OC} \quad \text{dollars}$$

where,

P_W = condensate pump power input = 20 watts,

Q = number of pumps = 3 and

W_{OC} = other components weight = 19.5 lbs

Substituting the values of the above variables in the pumps fabrication cost equation results in the following:

$$C = 91 \times 16.8 \times 2.66 + 670 \times 19.5 = 17,132 \quad \text{dollars}$$

Integrated Circulating KOH Electrolysis System's Recurring CER

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on typical cost breakdown ratios presented in Table II, which are based on actual cost data collected in a space vehicle hardware production program. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

$$\text{System design cost } C = 34,935N + 102,942 \text{ dollars}$$

The circulating KOH electrolysis system comprises 25 component types as shown in Table XII. Accordingly, system design cost $C = 873,375 + 102,942 = 176,317$ dollars. Values of other non-recurring cost items are listed in Table XII, which also shows the breakdown of recurring cost items based on the production of two flight hardware units.

TABLE XII - CIRCULATING KOH ELECTROLYSIS SYSTEM COST BREAKDOWN *

Non-Recurring		Recurring	
System Engineering Design	976,317	Flight Hardware Production (2 units)	721,004
Subcontractor General and Administrative	504,756	Subcontractor G&A	121,841
Subcontractor Fee	211,861	Subcontractor	51,274
Program Management	73,224	Program Management	17,972
System Engineering	307,540	Sustaining Engineering	25,901
Development Test	201,121		
Qualification Test	148,400		
Reliability Test	239,198		
AGE	1,079,807		
Tooling	226,506	Sustaining Tooling	22,333
Non-accountable Test Hardware	97,632		
Specifications, Vendor Coordination and Procurement Expense	797,651	Specification, Vendor Coordination and Procurement Expense	204,698
System Integration	489,135	System Integration	94,486
Prime's Testing	478,395		
Minor Subcontracts	22,455	Minor Subcontracts	61,978
Total	5,853,998		1,321,487
Total Circulating KOH Electrolysis System Cost = 1,321,487 + 5,853,998			
= 7,175,485 dollars			

* All costs in estimated January 1972 dollars.

Section 4

CONCLUSIONS

New methodology and cost estimating relationships were developed for flight-type and prototype oxygen recovery systems. Four oxygen recovery systems were considered. Two of the systems, Sabatier and Bosch are designed for the reduction of carbon dioxide to methane or carbon and water. The water produced in the CO_2 reduction system is electrolyzer in one of the two electrolysis systems evaluated to produce breathing oxygen. The electrolysis systems presented are the solid polymer electrolyte and the circulating KOH electrolyte. System costs were found to be directly proportional to system complexities and the number of components involved in each system. System comparisons should include all cost elements pertaining to operating system parameters, such as power, heat rejection, expendables, subsystem interfaces, and crew time so that all the systems considered would be compared on a common basis encompassing all the penalties incurred by each system on the spacecraft for the duration of the mission.

The most pertinent research and technology areas where additional efforts are warranted include the following:

1. Temperature control of the Sabatier system requires additional development.
2. Additional research and technology efforts should be expended to produce an operational high-fidelity Bosch CO_2 reduction system which provides high purity CO_2 , operates completely independent of gravity and has no carbon deposition problems.
3. The further development of the solid polymer electrolyte system to provide long-life system operation, preferably in manned integrated life support system test, should be accomplished.
4. Additional development and repackaging of the circulating KOH electrolyte system are required.

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